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Evolution of an impact-generated dust cloud and its effects on the atmosphere

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ABSTRACT

We have simulated the evolution of an optically thick dust cloud in the Earth's atmosphere and have also calculated the effects such a dust cloud would have both on the amount of visible light reaching the surface and on the temperature at the Earth's surface. The dust cloud simulations utilize a sophisticated 1-D model of aerosol physics. We find that large quantities of dust remain in the atmosphere for periods of only 3 to 6 months. This duration is fixed by the physical processes of coagulation, which cause micron-sized particles to quickly form and sedimentation that swiftly removes the micron-size particles from the atmosphere. The duration of the event is nearly independent of the initial altitude, initial particle size, initial mass, atmospheric vertical diffusive mixing rate, or rainout rate. The duration depends weakly upon the particle density and the probability that colliding particles stick together to form a larger particle. The duration is also limited by the rate at which the debris spreads from the initial impact site. The dust must be uniformly spread over a large fraction of the Earth within a few weeks or the duration of the event will be less than 2 months. We used a doubling code to calculate the visible radiative transfer in these dust clouds. We find that light levels are too low for vision for 1 to 6 months and too low for photosynthesis for 2 months to 1 year. Calculations of the surface temperature show that the oceans cool by only a few degrees owing to their large heat capacity. However, continental surface temperatures drop below freezing for approximately twice as long as sub-photosynthetic light levels persist. We speculate briefly upon several other effects that might occur after the dust clears due to widespread snowfields, enhanced H_2O amounts, or chemical changes in the atmosphere. We also speculate that low light levels would cause a collapse of the marine food chain and oceanic extinctions. Cold temperatures over the continents and low light levels would prevent some animals from finding food and would cause continental extinctions.

INTRODUCTION

Alvarez and others (1980) proposed that the Earth was struck by a large extraterrestrial body about 65 million years ago. The impact is thought to have injected large quantities of debris into the Earth's atmosphere, which subsequently reduced the amount of sunlight reaching the surface and thereby stressed the biological community perhaps causing it to collapse. In order to evaluate better the significance of such an impact, we simulate several impact scenarios. We calculate how long the dust would remain in the atmosphere, how much light would reach the surface as a function of time, and how the temperature of the surface would be affected. More extensive discussions of these calculations may be found in Toon and others (in prep.) and Pollack and others (1982).

In this report we first compare large meteorite impacts and volcanic explosions. Until now the Krakatoa eruption has served as a yardstick of the duration and magnitude of a meteorite impact, but this comparison is misleading. Next, we review the physical processes that effect dust in the atmosphere. We then simulate injections that distribute dust globally and follow by simulating injections that distribute dust only locally. Using these dust simulations, we calculate the amount of sunlight reaching the Earth's surface; then we determine the changes that would occur in the Earth's surface temperature.

The work discussed in this paper is built upon a number of theoretical calculations. We attempt to highlight the uncertainties in performing these calculations. We find that the conclusions are surprisingly robust. The results of the aerosol calculations might have depended upon a large number of parameters that are difficult to quantify, such as the rainfall rate. However, we find that the aerosol results are sensitive only to fairly well defined quantities such as particle density. The surface temperature calculations could have depended upon the details of particle size or composition, as is the case for volcanic calculations. However, we find that a strong surface cooling is forced by the nearly total loss of solar energy at the surface due to the dust cloud opacity. The ability of the calculations to place fairly narrow limits upon the possible scenarios after the impact is a surprising result that is an attractive feature of this problem. A major uncertainty in understanding the role of a general impact in causing extinctions is associated with the quantity of dust injected into the atmosphere, the area of the Earth initially covered by dust, and the ability of winds to distribute the dust horizontally before the dust is removed from the atmosphere. We discuss these problems in this paper. However, the fact that large quantities of dust are observed to have been globally distributed by the event studied by Alvarez and others (1980) eliminates the uncertainties connected with dust transport for this event. Other uncertainties, which do apply to that event, include the possibility of changes in atmospheric chemistry and climatic feedbacks in response to the dust loading. Such changes will not negate the effects of dust on temperature or surface-light levels. Most of these changes will be in addition to the effects of the dust or will be most important after the dust has cleared. Of course the major uncertainty with respect to extinctions is proper evaluation of the response of biological systems to changing environmental conditions.

VOLCANIC ERUPTIONS AND ATMOSPHERIC DUST

The characteristics of volcanic debris in the atmosphere are reasonably well known (Toon and Pollack, 1982; Toon and Pollack, 1976; Pollack and others, 1976, Lamb, 1970). Several authors have utilized volcanic eruptions to scale the quantity of debris in the atmosphere for a meteorite impact in order to deduce a typical heavy dust load duration and to estimate the global spreading rate of the dust.

For a few years after an eruption vivid twilights and other optical phenomena provide evidence of enhanced stratospheric aerosol levels. However, most of the long-lived debris consists of sulfuric acid particles generated photochemically from sulfur dioxide gas which was vented to the stratosphere by the volcano. The silicate ash injected by the volcano is removed from the stratosphere over a period of just a few months owing to the fairly large sizes of typical ash particles and their resulting large sedimentation velocities. Figure 1 illustrates the evolution of the dust mass following the 1963 Mount Agung eruption. The dust was removed in about 6 months. The size of meteoritic debris is likely to resemble that of volcanic debris. Hence, meteoritic dust is unlikely to remain in the stratosphere longer than a few months in analogy with observations after volcanic eruptions.

From observations of the optical depth after volcanic eruptions the mass of debris in the stratosphere may be determined. The optical depth is simply the negative of the logarithm of the direct transmission of sunlight and has been continuously measured since before the Krakatoa eruption (Pollack and others, 1976). The volume of debris in the stratosphere some months after the eruption of Krakatoa (1883), Katmai (1912), and Agung (1963) was only about 10^{-2} km^3, and most of this particulate volume was probably composed of sulfuric acid rather than volcanic ash (Toon and Pollack, 1982; Deirmendjian, 1973).

Alvarez and others (1980) incorrectly interpreted old reports of the Krakatoa eruption and thought that 4 km^3 of ash, which is 20% of the total ejecta volume, were hurled into the stratosphere and spread worldwide by winds. Alvarez and others (1980) used these numbers to deduce the volume of material ejected into the stratosphere

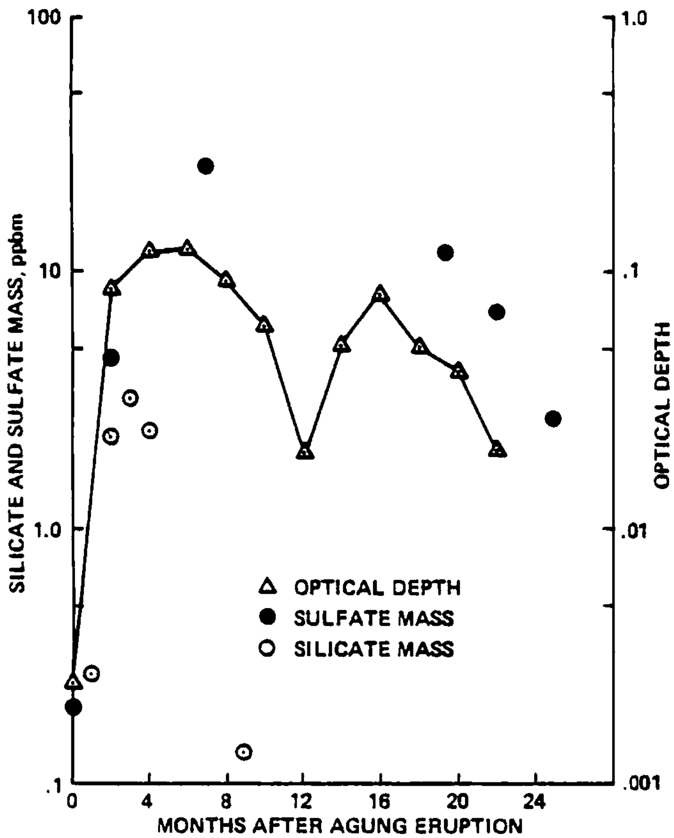

Figure 1. The mass of volcanic silicate ash, the mass of sulfate, and the optical depth are illustrated as a function of time following the Mount Agung eruption of 1963 (Toon and Pollack, 1982). The time evolution of sulfate matches that of the optical depth showing that sulfuric acid particles are primarily responsible for the "dust" veils seen after volcanic eruptions. The ash falls quickly from the stratosphere due to the relatively large particle size.

by a meteor impact. However, the error is probably of little consequence to their analysis. Impact studies relevant to meteorite impacts do suggest that in contrast to volcanic eruptions large quantities of meteoritic debris could be ejected into the upper atmosphere (Ahrens and O'Keefe, 1981).

The more serious problem with the Alvarez and others (1980) overestimate of volcanic ejecta volumes is that it led several investigators to challenge the asteroid hypothesis on the basis that large volcanic eruptions should have put comparable amounts of debris into the atmosphere. Kent (1980) scaled the caldera volume of the Toba eruption of 75,000 years ago to the volume of a meteorite crater and found that it should have injected a volume of debris into the stratosphere that was comparable to that injected by a large asteroid. More recently the Tambora eruption, thought to have caused 1816 to be "the year without a summer" (Toon and Pollack, 1982), would have injected 10% of the volume Alvarez and others (1980) suggested for a large asteroid.

Scaling arguments based on the correct volume of stratospheric debris injected by large explosive events would suggest that the injected masses from Tambora and Toba should be reduced by a factor of about 400 over those estimated by Kent (1980), making them much smaller events than the asteroidal ones. In addition, scaling arguments based on the comparison of volcanic caldera volume and meteorite crater volume may not be very reliable. For example, the energy of the events may be a more relevant scaling parameter. The kinetic energy of the asteroid discussed by Alvarez and others (1980) is equivalent to 10^8 megatons of TNT. This energy is 10^7 times larger than the mechanical shock energy of the May 18, 1980, Mount St. Helens eruptions or 10^6 times larger than the 1883 Krakatoa eruptions (Press and Harkrider, 1966; Colgate and Segurgeirsson, 1973; Decker and Decker, 1981). Considering energy released in all forms from the Mount St. Helens eruption, the asteroid is equivalent to 2.5×10^5 Mount St. Helens eruptions (Decker and Decker, 1981). If one scales the amount of debris injected by volcanoes on energy rather than on caldera volume, then huge deficits relative to the asteroid are evident.

Another important consideration concerning volcanoes is the rate at which volcanic debris is distributed over the Earth's surface. Typically, the debris circles the Earth within its own latitude band during a few weeks or months. The zonal stratospheric wind speeds and directions vary greatly with altitude, and debris nearest the tropopause usually is transported most rapidly (e.g., Danielsen, 1981). The north-south spreading of the debris is much slower. Although the debris from equatorial eruptions usually spreads over one or both hemispheres during a 6-month period, the material from high-latitude eruptions usually does not spread below 30° latitude in the hemisphere in which it is located. After the very large 1963 eruption of Mount Agung located at lat 8° S., 9 months passed before dust reached the South Pole (Lamb, 1970), and very little debris ever entered the Northern Hemisphere (Toon and Pollack, 1982).

The spread of volcanic debris probably is not a good analog for a large meteorite impact. The quantity of debris injected by observed volcanic eruptions has been rather small and has had only a minor impact on stratospheric temperatures. For example, Southern Hemisphere stratospheric temperatures increased by only a few degrees Centigrade after the Mount Agung eruption. This increase is only a few times greater than the natural annual variability of stratospheric temperatures (Toon and Pollack, 1982). An immense debris cloud from an asteroidal impact would have a strong influence on the stratospheric thermal structure which would overwhelm the normal dynamics and induce wind fields tending to spread the dust into a horizontally uniform dust distribution.

A good analogy to the spreading after an asteroid impact may be the rapid spread of martian dust storms. The atmospheric mass on Mars is comparable to that of the Earth's stratosphere above 30 km. Hence, the time required for dynamic response to radiative perturbations in the martian atmosphere should be comparable to that required in the Earth's stratosphere where the asteroidal dust would be concentrated. Observations show that martian dust storms grow from local to nearly global coverage in only a week or two (Pollack and others, 1979). The idea that this spreading is due to expansion of a local dust cloud is supported by theoretical models. The models show rapid expansion driven by radiative heating in the dust which induces a strong circulation (Haberle and others, 1982).

We conclude from the volcanic analogy that asteroidal dust is not likely to remain in the stratosphere more than a few months. Asteroid impacts may hurl much larger quantities of dust into the upper atmosphere than volcanic eruptions with smaller caldera volumes, because asteroid impacts are much more energetic than volcanic eruptions. Debris from a large asteroid impact would probably induce a stratospheric wind system tending to quickly spread the debris over the Earth. This dust spreading would be more similar to martian dust storms than to volcanic events on Earth.

PHYSICAL PROCESSES AFFECTING SUSPENDED PARTICLES

After a collision between a meteorite and Earth, large quantities of dust would be injected into the atmosphere. Winds would then redistribute the dust over the globe. The dust originally in the lower atmosphere would be quickly removed by rainfall and by sedimentation of the larger particles. The dust in the stratosphere would also be removed by sedimentation except for the fraction which is smaller than about 0.5-μm radius. Such small particles are normally removed by dynamical transport to the lower atmosphere. After a massive injection of dust, however, coagulation would play a more important role than for normal aerosols. Small particles would coagulate owing to their Brownian and gravitational motion and would form larger particles which would then be removed by sedimentation.

Simulating the injection of dust into the atmosphere by an asteroid impact is beyond the scope of the present work. We begin our calculations after the dust has already been placed into the atmosphere and has lost the energy of the initial injection. It takes very little time for the dust to reach equilibrium. If the dust traverses an atmospheric mass that is slightly larger than the dust mass, then viscous forces will transfer the original energy of the dust to the atmosphere. For example, single meteoritic particles of 100-μm radius entering the atmosphere typically ablate completely above 90-km altitude (Hunten and others, 1980). Even if all the debris thought to be injected 65 million years ago, about 1 g cm^{-2} spread over the Earth's surface (Alvarez and others, 1980), were thrown into orbit and reentered the atmosphere at high velocity, the dust would come to equilibrium due to gas drag between 30- and 50-km altitude. Likewise, if the dust were ejected horizontally from the impact site, viscous drag would have stopped the dust before it reached about 500 km from the impact site. Emiliani and others (1982) showed that dust blown vertically would come to rest in the upper stratosphere due to gravitational potential energy. Hence, the initial energy of the dust is quickly dissipated, and the dust cloud can be treated theoretically without explicitly including effects due to the blast very soon after the impact.

If a mass equivalent to 1 g cm^{-2} of dust spread over the Earth's surface were distributed in the atmosphere as a 30-km-thick dust cloud, then the mass density would be about 0.3 g m^{-3}. Fair weather cumulus clouds often have mass densities of 1 g m^{-3}, and cumulonimbus clouds have mass densities several times larger (Mason, 1971). Hence, the physical processes controlling the dust cloud after a large impact are similar in many ways to those controlling clouds. The physics of the dust cloud is much simpler than that of the water cloud because condensational growth does not occur in the dust and many of the complexities of cloud physics are due to condensational growth.

These physical processes for a dust cloud can be represented by a continuity equation:

$$\begin{aligned} d\,C(v)/dt &= -d/dz\,(\phi_s + \phi_d) \\ &+ 1/2 \int_0^v K\,C(v-v')\,C(v')\,dv' \\ &- \int_0^\infty K\,C(v)\,C(v')\,dv' \\ &- C(v)/\tau_r - C(v)/\tau_d \end{aligned} \qquad (1)$$

In this expression the rate of change of the concentration (C) of particles of volume (v) is controlled by: the vertical gradient of the sedimentation (ϕ_s) and eddy diffusion fluxes (ϕ_d), the production of particles of volume (v) by coagulation of smaller particles which is controlled by a coagulation kernel (K); the loss of particles of volume (v) by coagulation with particles of other sizes; the removal of particles by rainout at a rate of τ_r; and the removal of particles by horizontal transport away from the initial impact site at a rate τ_d.

Toon and others (in prep.) described the physical expressions for the various terms in the continuity equation for dust. Hamill and others (1977), Turco and others (1979), and Toon and others (1979) also provided relevant information.

Figure 2 summarizes the relative magnitudes of some of these terms and allows one to understand how the basic physical processes operate. In Figure 2, τ_r is the time required for rainfall at current rates to remove aerosols to e^{-1} of their initial concentration; τ_e is the time for vertical eddy diffusion to transport particles 10 km; τ_f is the time for particles of a given size to fall 10 km; and τ_c is the time for 10^3 monodisperse particles of the same size to coagulate

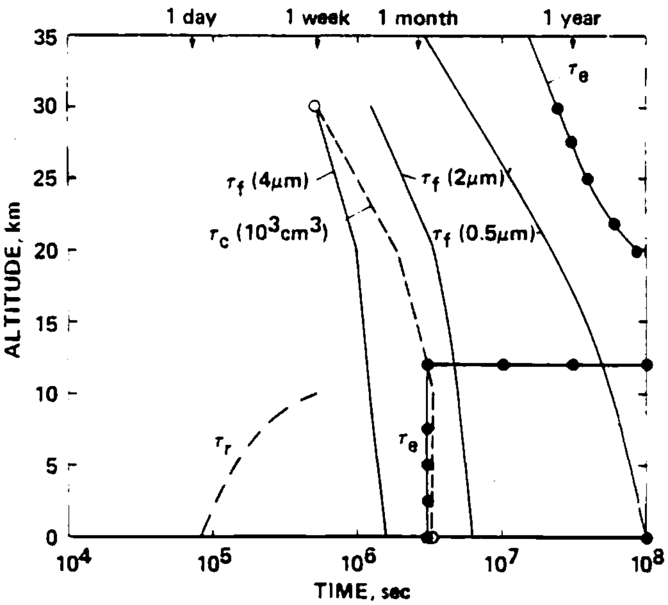

Figure 2. The rates at which various processes affect the concentration of dust at various altitudes. τ_r is the time for rainfall to reduce the dust concentration to e^{-1} of its initial value. τ_e is the time for vertical mixing to transport material 10 km assuming a standard eddy diffusion profile (Turco, and others, 1979). τ_f is the time for a particle of given size to fall 10 km assuming spherical particles of density 3 gm cm^{-3}. τ_c is the time for coagulation owing to Brownian motion to reduce 1,000 particles of 0.5 μm radius to 500 particles of larger size. Sedimentation rates of 2- to 4-μm-size particles are so rapid that particles of such size will be quickly removed even if rainfall and vertical mixing do not occur. At large dust masses there are so many particles present, if they have small size, that coagulation will rapidly produce large particles.

owing to Brownian motion and produce 500 larger particles.

Figure 2 shows that in the troposphere (below ≃ 12 km), rainfall in the present-day atmosphere is so rapid that particles will be removed in only a few days. If rainfall were to cease, diffusive transport would carry tropospheric particles to the ground in only a month. Even if no rain falls and all vertical winds and turbulence cease, as might occur in the extreme case of a darkened atmosphere with an isothermal troposphere, tropospheric particles with radii larger than about 2 μm will still fall to the ground in only a few months.

In the stratosphere, rainfall does not occur and vertical transport is not very effective. Particles larger than 0.5 μm fall out of the stratosphere in about 1 year, while slightly larger particles will be removed much faster. The rate at which particles collide owing to Brownian motion is very large if 10^3 particles cm^{-3} are present. The typical mass densities suggested for a large asteroid impact (1 g cm^{-2}) would yield about 5 x 10^4 particles cm^{-3} of 0.5-μm size over a 30-km vertical column. Such particles would quickly coagulate to form particles of larger sizes and then would be removed by sedimentation.

The time constants in Figure 2 make it clear that the physical processes governing the dust are dominated by sedimentation and coagulation. The dominance of these two processes greatly simplifies the physics and reduces the dependence on processes that are difficult to evaluate, such as rainfall. If particles are as large or larger than 2 μm, they will fall from the atmosphere within a few months, irrespective of rainfall or vertical-transport rates. If the particles are smaller than 2 μm, their large numbers will cause rapid coagulation and the subsequent production of large particles.

The calculations reported here do not include gravitational coalescence. Coalescence does not occur for particles smaller than about 5 μm owing to hydrodynamic flow of small particles around larger ones (Mason, 1971; Twomey, 1977). Elsewhere (Toon and others, in prep.) we present calculations in which coalescence is included and show that it does not affect the results presented here.

A major uncertain parameter in these calculations is the probability that two particles colliding owing to Brownian motion will stick together and form a larger particle. Experimentally it is found that collisions between solid particles of submicron size result in sticking with nearly 100% efficiency (Fuchs, 1964; Twomey, 1977). The physics of this sticking is not well understood, but it is largely caused by Van der Waals–London forces (Twomey, 1977). In our calculations we explore the consequences of a reduced sticking probability.

SIMULATIONS OF THE EVOLUTIONS OF DUST CLOUDS

We solve the continuity equation (1) with a time dependent, one-dimensional model similar to the one employed by Turco and others (1979) and Toon and others (1979) to simulate the Earth's stratospheric aerosol layer, by Turco and others (1982b) to simulate noctilucent clouds, and by Hunten and others (1980) to study meteoric debris in the Earth's atmosphere. The model has been shown in these studies to be realistic enough to duplicate successfully observed aerosol-size distributions and vertical distributions in geophysical situations.

For the present simulation the model considers 54 vertical levels, each 2 km thick, extending from the surface to 108-km altitude. Forty-five size categories of aerosols are treated, ranging from 10 Å to 26 μm in radius in a series of model bins each of which contains twice the volume of the bin below it. An aerosol sink occurs at the ground, and no flux occurs across the model's top level. The model is initialized using conditions appropriate to the impact event as described in Table 1. Then using a variable time step, which allows only modest changes in aerosol properties to occur

TABLE 1. VARIABLE PARAMETERS

Parameter	Standard	Variation	Sensitivity
I. Atmospheric structure			
Vertical mixing	Current Earth diffusion coefficients	None	Slight
Rainout rate	Current Earth profile	None	Slight
Horizontal transport time	Not included	2 weeks 1 month 2 months	Large
II. Particle properties			
Density, ρ	3 g cm^{-3}	1 g cm^{-3}	Moderate
Coagulation efficiency, α	1.0	0.1 0	Slight Large
III. Initial conditions			
Injection altitude	12-42 km	60-88 km	Slight
Mass injected	1 g cm^{-2}	10 g cm^{-2} 0.1 0.01	Slight Slight Slight
Size distribution, r_m (Lognormal σ = 1.8)	0.5 μm	0.005 μm 5 μm	Slight Large

in a given step, the model is run until most of the debris is removed from the atmosphere.

A number of variations to the physical processes in the model and to the initial conditions of the dust cloud can be hypothesized. We establish a standard case and then perform calculations varying one parameter at a time in order to understand how sensitive the results of the calculations might be to our assumptions. Table 1 describes the various parameters in the model and indicates our judgment of how sensitive the calculations are to the variations. We judge sensitivity based on the duration of optical depths larger than 10. We chose the duration of large optical depths because the period of time without light is critical to the surface temperature and to photosynthesis. An optical depth of 10 was chosen based on transmission calculations. Figure 3 shows the amount of light reaching the surface for various optical depths. An optical depth of 10 yields transmissions that are barely adequate for photosynthesis.

Figure 4 illustrates the calculated optical depths as a function of time for several of the cases outlined in Table 1. If we assume that the initial particle size is about 5 μm (r_m = 5 μm), then the particles quickly fall out of the atmosphere, and an optical depth of 10 is reached in only a month. If we assume that the initial particle size is 0.5 μm and the particles do not coagulate (α = 0.0), then the optical depth of 10 is not reached for several years. Neither of these assumptions is realistic, but they illustrate the importance of coagulation and sedimentation in determining the fate of the dust.

A realistic assumption is that the particle size is initially the same as that of volcanic dust. It has been found that windblown dust on Earth and Mars and volcanic debris all have the same characteristic size of about 0.5 μm, which is due to the physical resistance of rock to being broken into smaller fragments (Toon and others, 1977; Pat-

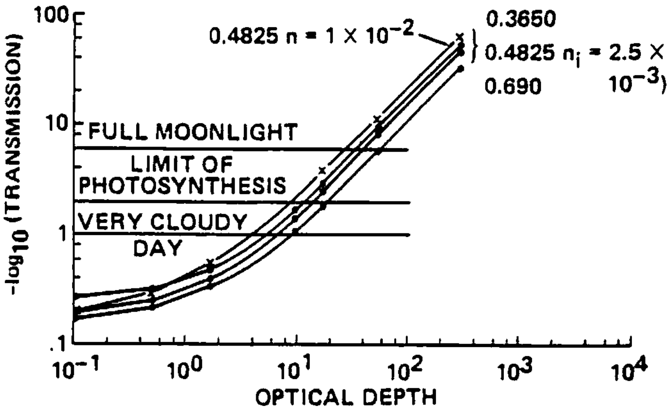

Figure 3. The logarithm (base 10) of the transmission of visible light is shown as a function of the optical depth at 0.55 μm wavelength. The transmission is shown for three wavelengths that span those significant for photosynthesis using a dust imaginary index of 2.5 x 10^{-3}. The transmission for a higher index of 10^{-2} is also shown for one wavelength. The transmission levels equivalent to three significant natural phenomena are indicated.

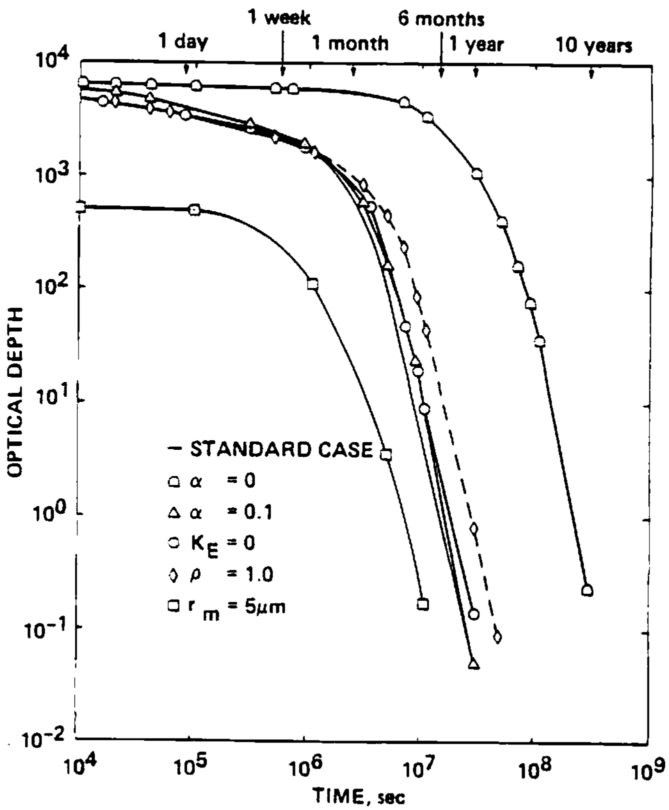

Figure 4. The visible optical depth (0.55 μm) is shown as a function of time for several different scenarios after an impact. α is the coagulation probability, ρ is the particle density, K_E is the vertical eddy mixing coefficient, and r_m is the mean particle size. Large particles are removed in a few weeks. If coagulation does not occur, the particles remain small and are removed over several years by dynamics. Reasonable variations in the parameters yield similar durations of 3 to 6 months for large optical depths.

terson and Gillette, 1977, Farlow and others, 1981). It is also realistic to assume that coagulation occurs very efficiently. These assumptions are made in the standard case, and Figure 4 shows that the duration is limited to about 100 days. If vertical mixing is stopped ($K_E = 0$), if the particle density (ρ) is reduced from 3.0 to 1.0, or if the coagulation efficiency (α) is reduced to 0.1, it does not greatly alter the results from the standard case.

Figure 5 illustrates other calculations in which the debris is injected from 60- to 80-km altitude rather than from 12- to 42-km altitude and in which the original mass is injected as 5-Å-size molecular clusters. These cases also differ only slightly from the standard case. Toon and others (in prep.), have derived the dependence of the particle size and optical depth on altitude and time for several of these calculations.

Figure 6 illustrates the dependence of the duration of the optical depth on the initial mass loading. The standard case assumes that 1 g cm^{-2} of meteorite and ejecta debris is uniformly spread in the stratosphere. This mass is comparable to that assumed by Alvarez and others (1980) who suggested that there was 1 cm of total debris at the Gubbio site and about 60 times less material of pure meteoritic origin. The global mass of material corresponding to 1 g cm^{-2} is about 5×10^{18} g. In Figure 6 the duration of the event does not strongly depend upon the mass. Even masses as small as 100 times less than 1 g cm^{-2} yield optical depths much larger than 10.

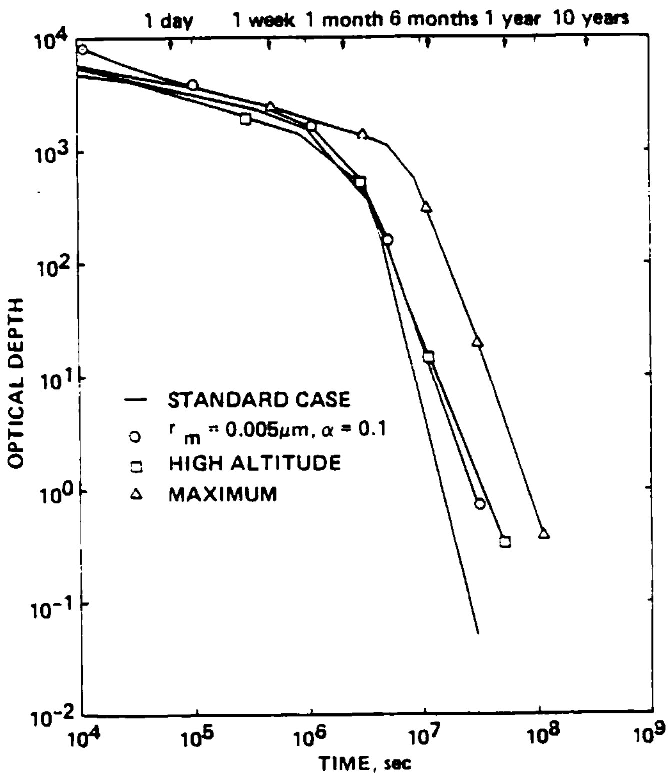

Figure 5. As in Figure 4. High altitude indicates an injection above 60 km. MAXIMUM is a case with no rainfall, no vertical mixing, a low particle density and reduced coagulation efficiency. MAXIMUM represents the longest possible duration of large optical depths.

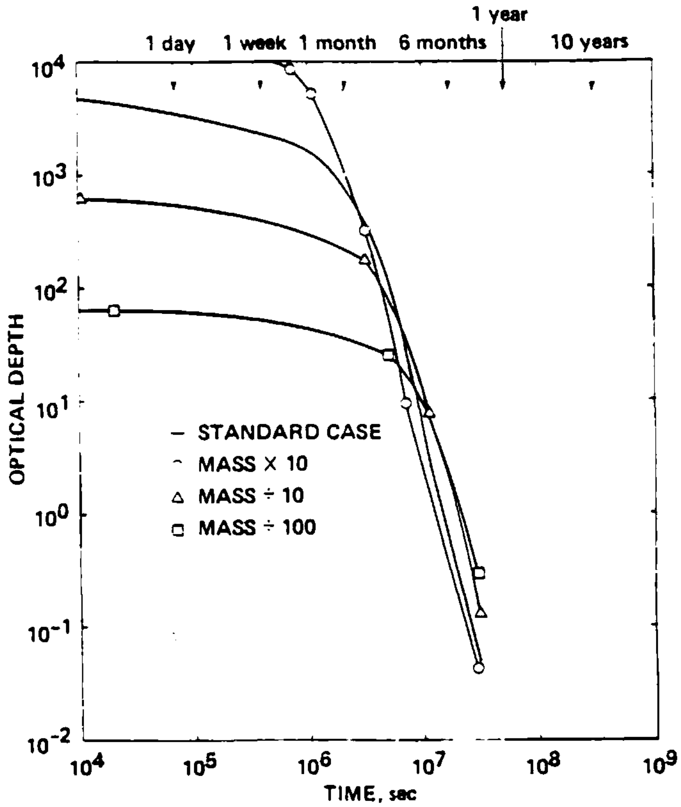

Figure 6. As in Figure 4. The standard mass is equivalent to 1 g cm^{-2} spread uniformly over the Earth. The duration of large optical depths is not very sensitive to the injected mass.

Although most of the cases studied have produced less than 6 months durations with optical depths of greater than 10, it is possible to obtain slightly longer durations. Such a case is illustrated in Figure 5 by the curve labeled "MAXIMUM." Here we assumed that the particle density was 1, that neither rainfall nor vertical mixing occurs, and that the coagulation efficiency is 0.1. This case has the maximum reasonable duration of large optical depths of almost 1 year.

In all the simulations shown in Figures 4 through 6 we have assumed that a certain amount of debris was present over the entire Earth, but have ignored the changes in dust loading which might occur as the dust spreads over the Earth. Figure 7 illustrates calculations in which a finite spreading time is considered. These calculations are most relevant for the change in optical depth at the general location of impact site. We assume that after a certain time, given in the figure captions, the debris will be uniformly spread over the Earth. If no loss processes occurred, the coverage after the spreading time was reached would be 1 g

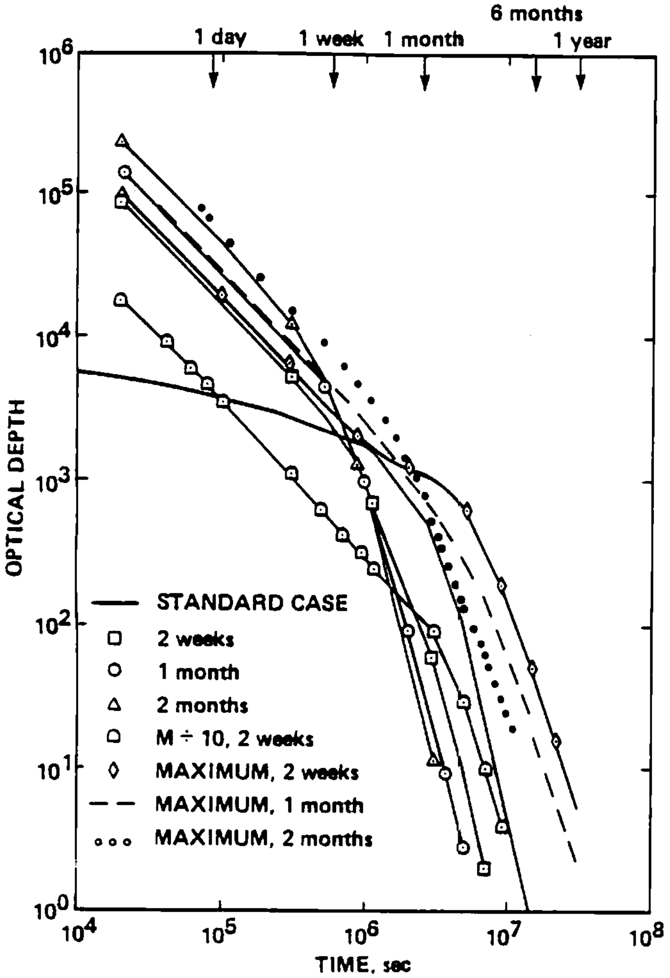

Figure 7. As in Figure 4. The times given in the key indicate the time taken before the debris is uniformly spread over the Earth. The area covered by debris is assumed to vary linearly with time beginning 1 hour after impact and continuing until the Earth is uniformly covered. The standard cases and the reduced mass case do not produce large optical depths over the entire Earth unless the spreading time is 2 weeks or less. Such times are plausible based on the martian analogy (Haberle and others, 1982). Since dust is found over the entire earth due to the event discovered by Alvarez and others (1980), such a global debris cloud must have occurred.

cm^{-2} (except for the M ÷ 10 case). The spreading occurs in a manner such that the area covered by dust increases linearly with time.

A factor that is not considered in our calculations is winds induced by the mass loading of the atmosphere. If 1 g cm^{-2} of debris is concentrated over 1% of the Earth's surface (a 1,200-km-diameter region), its mass would be 100 g cm^{-2}. The mass of the whole atmosphere is only about 10^3 g cm^{-2}, and the mass of the stratosphere is about 10^2 g cm^{-2}. Hence, such meteoritic mass loadings represent substantial increases to the atmosphere mass. Increased atmospheric mass would create hydrodynamic density flows like those observed on the slopes of volcanoes, and the debris would rapidly flow to lower altitudes and also spread horizontally. We believe that unless the ejecta is transported ballistically, or by impact-induced flows to distances well beyond 1,000-km diameter, substantial quantities of debris will not remain in the atmosphere.

Figure 7 shows that the enhanced coagulation that occurs in the dense spreading debris cloud limits the amount of dust available at the time when global coverage is reached. The most probable cases reach optical depths of 10 in only 1 to 2 months. If the spreading time is not less than 2 weeks, then the last places on Earth to be covered will experience optical depths of less than 10. Reducing the mass by a factor of 10 does eliminate some of the coagulation, yielding slightly smaller particle sizes and slightly longer durations. The cases labeled "MAXIMUM," which are similar to the one described earlier, show smaller effects due to the horizontal spreading. For example, the MAXIMUM 2-WEEKS case has the same optical depth as the standard case after 2 weeks. Thus, it is possible to obtain large optical depths for as long as 6 months after the event if one wishes to make relatively extreme assumptions about the density of the dust (1.0) and the lack of both rainfall and vertical mixing. The event studied by Alvarez and others (1980) is observed to have resulted in debris covering the entire Earth with great enough mass for large global optical depths.

We summarize our conclusions from these dust evolution studies as follows. The physics is dominated by coagulation and sedimentation so that the duration of the event is not sensitive to most of the initial conditions and atmospheric parameters (Table 1). The duration of large optical depths is probably shorter than 6 months and is most likely less than 3 months. It is highly improbable for substantial quantities of debris to have remained in the atmosphere for more than a year. Very short durations will occur unless horizontal transport is very rapid, but rapid transport is likely based upon the Mars dust-storm analogy. The duration of the event is not sensitive to the injected mass as long as it is within a factor of 100 of 1 g cm^{-2}. The initial optical depths are very large, being 6×10^3 for 1 g cm^{-2} and 60 for 0.01 g cm^{-2}, assuming that the dust has an initial size of 0.5 μm. Finally, it is important that the initial impact spread dust over a large area of the Earth. For 1 g cm^{-2} of ejecta the area needs to be much greater than 1% of the Earth's surface area to prevent hydrodynamic flows from quickly depositing the debris at the surface. Since 1 g cm^{-2} debris is observed worldwide by Alvarez and others (1980), global coverage with large optical depths occurred for that event.

CALCULATIONS OF LIGHT REACHING THE SURFACE

Figure 3 illustrates the calculated relationship between the global average amount of sunlight reaching the surface and the dust optical depth. These calculations were made using a doubling-adding code, which, in principle, is an exact solution (Pollack and others, 1976). The particle-size distributions were obtained from the standard case (except $\alpha = 0.1$), so the size varies slightly as the optical depth changes. We performed calculations for wavelengths from 0.365 to 0.690 μm which span the range of wavelengths utilized by plants (Gerstl and Zardecki, 1981; McCree, 1971). The transmission increases with increasing wavelength partly because the optical depth decreases with wavelength but mainly because the refractive index of rock typically has a declining imaginary part with increasing wavelength (Patterson, 1981a). The dust imaginary index of refraction was chosen to be 2.5×10^{-3} at 0.55 μm in agreement with observations of stratospheric ash following the Mount St. Helens eruption (Patterson, 1981a) while a larger value of 10^{-2} was also explored since some crustal materials have such large refractive indices (Patterson, 1981b). As the imaginary index increases, the transmission decreases because the dust absorbs more of the light.

Figure 3 also presents several light levels of interest. The full moon light level is precisely known. The darkest night measured in England has -log of transmission about equal to 9 (Pirenne, 1962). The absolute threshold of dark-adapted human vision for a large field is only about -log of transmission equals 10, while for cats the threshold is about -log of transmission equals 11 (Pirenne, 1962). The light level on a cloudy day depends upon the cloud thickness, but the one shown represents a very cloudy day. In general, clouds transmit more light than dust for a given optical depth because large water drops are more strongly forward-scattering and less absorbing than smaller dust particles. Also a given mass of cloud has a smaller optical depth than the same mass of dust because the cloud particles are typically at least 10 times larger than dust particles and the optical depth is roughly inversely proportional to particle radius for fixed mass.

The level at which photosynthesis ceases is not well known and undoubtedly varies with species. Generally, photosynthesis proceeds at one-half the saturated rate at about 10% of the solar constant (Campbell, 1977). We assume that at 1% light levels photosynthesis will cease. Some organisms can survive on lower light levels. For example, blue-green algae in ice-covered Antarctic lakes photosynthesize at 0.1% of the surface-light levels (Young, 1981). Our assumption is not critical since light levels are well below 1% in most of our calculations.

Applying the transmission calculations of Figure 3 to the dust optical depth calculations of Figures 4, 5, 6, and 7 allows one to determine the time history of low-light levels. Figure 8 illustrates such calculations as applied to the dust-loading cases of Figure 6. For all mass loadings shown, not enough light reaches the surface for photosynthesis to

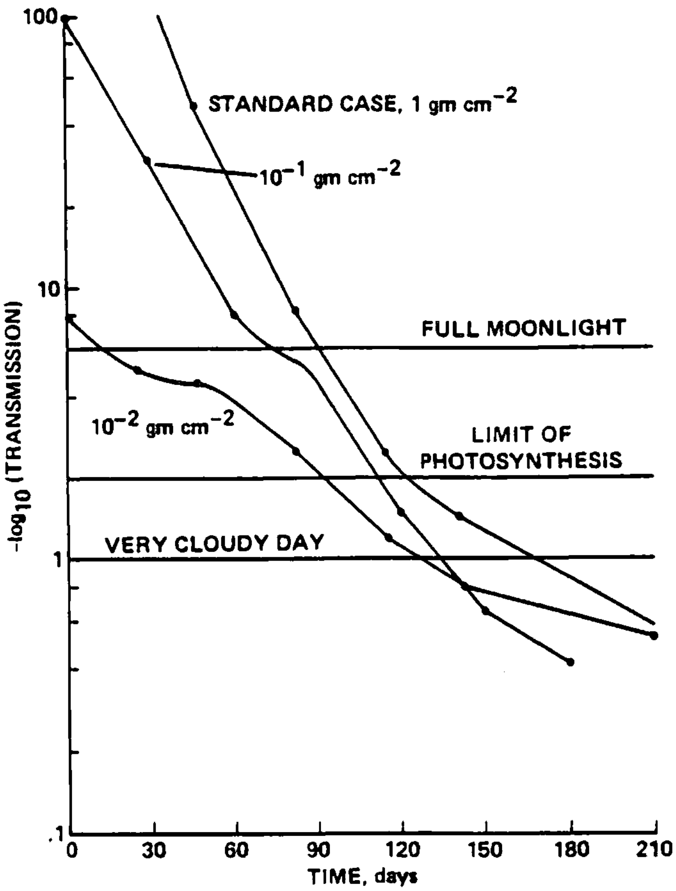

Figure 8. The logarithm (base 10) of the transmission of visible light is illustrated as a function of time for various mass loadings. Using Figure 3 and 4 to 7, the reader can construct similar figures for other cases. The transmission levels equivalent to three natural phenomena are indicated. For the larger two mass loadings, not enough light reaches the surface to allow vision for several months. Photosynthesis could not occur for any of these cases for about 3 months.

occur for 3 months or longer. For the larger mass loadings not enough light is available for vision for about 2 months.

We conclude that for greater than 0.1 g cm^{-2} of dust the light level is below the level of vision for 1 to 6 months, 2 months being most likely. For greater than 0.01 g cm^{-2} of dust the light level is below the threshold of photosynthesis for 2 months to 1 year, but 3 months is most likely.

CALCULATIONS OF SURFACE TEMPERATURES

Using the distributions of dust calculated in Figures 4 to 6, it is possible to find the changes in the Earth's radiation budget and thereby to estimate the changes in the global temperature. Similar calculations have previously been performed for volcanic eruptions (Pollack and others, 1976; Pollack and others, 1981, Hansen and others, 1978), and despite the simplicity of the calculations, it has been found that the observed temperature changes agree well with calculated ones. Likewise, terrestrial models applied to other planets with greatly different atmospheres, such as Venus, yield the observed temperatures (Pollack and others, 1980). Of course, complete analysis of the climate under perturbed conditions is not currently feasible, since no climate model is yet able to reliably predict precipitation patterns or regional climate changes.

Here we utilize the visible and infrared models of Pollack and others (1976) to estimate the effect of massive dust loads on the atmospheric thermal structure. These calculations, which are based upon very detailed radiative transfer calculations, are described in greater detail by Pollack and others (1982) and Toon and others (in prep.). Using the dust properties described previously, the solar energy deposition rates are calculated for several dust optical depths. Next the infrared cooling rates and the temperature dependence of the infrared cooling rates are calculated for the same optical depths. For the infrared calculations we used the optical constants of basaltic glass (Pollack and others, 1973), which are similar to those of a wide variety of terrestrial rocks (Patterson, 1981b). The temperature was assumed to be that appropriate to current ambient conditions for the infrared calculations. Finally, a time-marching code was used that began with an ambient thermal structure and altered it with time in response to the radiative imbalance between the infrared and solar energy supplies. The infrared cooling rates were adjusted to the thermal structure at a given time using the calculated temperature dependence of the infrared cooling rates. Both infrared and solar energy deposition rates were logarithmically extrapolated over optical depths to correspond to the temporal variation of optical depth as calculated in Figures 4 to 6. Energy was exchanged between adjacent atmospheric layers whenever the lapse rate exceeded 6.5 °C km^{-1}. The time-marching model accounted for the heat capacity of the air and the surface. Calculations were done both for a continental simulation, in which it was assumed that the ground surface instantly adjusted to the atmospheric temperature, and for an ocean simulation in which it was assumed that a 75-m-deep mixed layer of the ocean also responded to the thermal forcing. Calculations were also done for two different sets of the visible imaginary refractive indices of the dust. As Figure 9 shows for the standard case, the smaller refractive index case raised the albedo of the Earth above its normal value of about 0.3 for 50% cloud cover, and the high refractive index case lowered the albedo. Hence, in the former case the Earth-atmosphere system received a decreased amount of solar energy, and in the latter case it received more solar energy.

It is simple to anticipate the effect of the dust on the Earth's temperature. The Earth's climate is controlled by a balance between the solar energy absorbed by the atmosphere and surface and the infrared energy radiated to space.

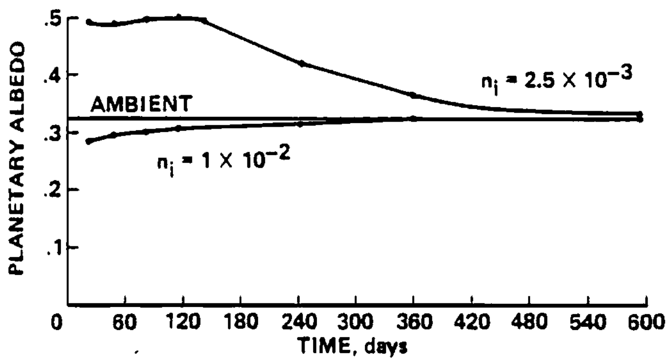

Figure 9. The Earth's albedo as a function of time for the standard case (but with $\alpha = 0.1$), using two values for the absorption of dust. The more absorbing dust causes the Earth-atmosphere system to absorb more sunlight than normal, and the less absorbing dust causes less sunlight to be absorbed than normal. In either case the sunlight is absorbed so far above the surface that a cooling occurs at the Earth's surface. The Earth is assumed to be 50% cloud-covered in these calculations.

Currently, the solar energy is mainly absorbed at the ground, since the atmosphere is nearly transparent at visible wavelengths, while the infrared energy is radiated from the upper troposphere, since the lower atmosphere is highly opaque at infrared wavelengths. The mean surface temperature, about 288 °K, is much higher than the mean emission to space temperature, 252 °K, because the opaque gases do not allow the surface to efficiently lose energy. At times of heavy dust loading, the infrared emission level lies slightly below the solar energy deposition level because both are controlled by the dust. Both levels are located in the stratosphere between 20- and 30-km altitude. Hence, the stratosphere quickly obtains the radiation to space temperature. The surface no longer receives any solar energy and has a net energy deficit. Therefore the surface cools. The lower stratosphere and upper troposphere receive some infrared radiation from the upper stratosphere and warm slightly. If large dust optical depths persisted indefinitely, the lower atmosphere would become isothermal at the emission to space temperature. In effect, the Earth would behave like a thermally insolated, black body that receives a fixed radiative energy input and responds by having a uniform temperature throughout its bulk so that its surface radiative energy loss balances the energy gain.

Figure 10 presents calculated surface temperature changes for several of the scenarios described in Figures 4 to 6. For the ocean, the large heat capacity prevents temperature changes from occurring rapidly. During the short time when no sunlight reaches the surface, the temperature of the ocean declines only a few degrees. Over the continents, however, sub-freezing temperatures occur for all the scenarios considered. For the standard case with either choice of refractive index, as well as for 10 times less mass than the standard case, the duration of sub-freezing

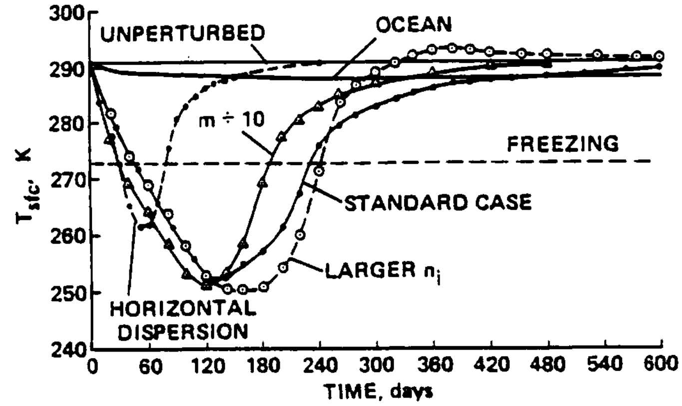

Figure 10. The surface temperature for an ocean simulation and for a continental simulation are illustrated as functions of time following a large impact. Several cases are shown for the continental simulation, all of which lead to dramatic coolings that persist for twice the time that the dust remains in the atmosphere. The large heat capacity of the ocean prevents it from cooling quickly.

temperatures is about 6 months. For the 2-WEEK STANDARD horizontal dispersion case, sub-freezing temperatures occur for about 45 days. In general, sub-freezing temperatures last for twice as long as the duration of darkness.

Hunt (1976) has performed general circulation model calculations for a continent-covered Earth in which the sunlight is shut off. His results for the rate of surface temperature decrease are similar to ours, although his case is not radiatively an exact parallel to the one considered here.

It is interesting to note that calculations for volcanic dust injections show that whether the Earth warms or cools depends sensitively upon the particle properties. Such is not the case for the heavy dust loading calculations. The total absence of sunlight at the surface forces the surface to cool. It is interesting that the higher imaginary index case (Fig. 10) leads to a slight surface warming a year after the impact when the optical depths are reduced to volcanic levels.

We conclude that very low temperatures are inevitable over the continents if very large amounts of dust are present in the atmosphere for even a few months. The duration of sub-freezing continental temperatures is about double the duration of optical depths exceeding 10. Ocean temperatures cannot fall more than a few degrees during a few months period without sunlight. An optically thick dust cloud from an asteroidal impact has a different affect on the radiation budget than an optically thin volcanic dust veil in that the surface temperature cannot increase for large optical depths.

SPECULATIONS

The decrease in surface temperature that we have found seems to us to be unavoidable if large quantities of dust are suspended in the atmosphere for several months. A number of possible changes might occur in the atmosphere, however, *after the dust clears*. Also some affects in addition to those due to dust may occur.

Sub-freezing temperatures for 6 months over the entire globe could possibly lead to extensive snowfield buildup over large areas of the continents. Such snowfields would greatly increase the albedo of the Earth and could sustain themselves indefinitely. The problem of the ice-covered Earth has been investigated many times, and it has been generally concluded that with the present solar luminosity an ice-covered Earth represents a stable climatic condition (Lindzen and Farrell, 1977; Budyko, 1969). Evidently the Earth did not permanently freeze over 65 million years ago, but it may have been fortunate not to have done so.

The major factor controlling whether or not total freezing occurs is undoubtedly the duration of cold temperatures. Unless a critical amount of snow develops and unless the oceans cool by a critical amount, the Earth will be able to recover. The critical duration is not known and to our knowledge has never previously been considered. It is certainly longer than several months because the Earth recovers every winter. The Earth is also able to recover from extensive ice fields that develop during the 10^5 years of an ice age, so it is potentially very resistent to freezing over.

A maximum depth of snowfield can be obtained by equating the latent heat of vaporization plus fusion for water to the amount of solar energy that would normally reach the surface without a dust cloud. This calculation suggests that the thickness of ice would have to increase at a rate of 0.5×10^{-2} cm min^{-1} to prevent the surface temperature from dropping. If the solar energy is removed for 3 months, then about 6 m oi snow at maximum could cover the continents. It should also be noted that any snow formed would be extremely "dirty" because of the large number of dust particles present. This effect would substantially lower the surface albedo and enhance the melting of the snow when the sunlight returned. The combination of this effect with the short duration of the event suggests that an asteroid impact is unlikely to trigger an ice age.

A precise calculation of the depth of snow after a large impact event would require sophisticated modeling of the climate which occurs under low-light levels. Such calculations would also be of great interest to determine the role of atmospheric heat transport that would remove heat from the oceans and carry it to the continents, preventing the continental surfaces from dropping to very low temperatures. Current extreme winter-time temperatures over the continents indicate that the oceans are not very efficient at preventing continental temperatures from dropping except in coastal areas.

Another possible scenario after the removal of the dust from the atmosphere is a great increase in temperature due to enhanced stratospheric water vapor amounts as suggested by Emiliani and others (1982). The worldwide abundance of iridium requires that large quantities of dust were present in the atmosphere after the impact event. The addition of water vapor would not alter our conclusions concerning immediate low temperatures, because the dust would prevent sunlight from reaching the surface. The increased infrared opacity of the water would simply augment the dust infrared opacity and could not cause a surface warming. After the dust was removed by sedimentation, however, large quantities of water might remain in the atmosphere. Without dust, sunlight would reach the surface and a "greenhouse" heating could occur.

The water hypothesis is difficult to assess. If one imagines that the impact-generated vapor immediately forms a cloud and rains out until saturation is achieved, as is highly likely, then the impact column will contain about 1 cm of H_2O cm^{-2} (Emiliani and others, 1982). If the impact column covers 1% of the Earth, then horizontal spreading would reduce the column water amount to about 10^{-2} cm of water, which is about 1% of the dust mass suggested by Alvarez and others (1980). At a moderate relative humidity, dust is highly adsorbing. Pulverized basalt, which is an order of magnitude less adsorbing than other minerals such as clays, can adsorb 1% of its weight in water at 50% relative humidity (Fanale and Cannon, 1974). Hence, it is quite possible for the water to be removed along with the dust.

An additional complication of the water-vapor hypothesis is that the thermal structure of the atmosphere is strongly coupled to the H_2O budget. After the dust has been removed, large quantities of injected water will strongly cool the upper atmosphere. As well, the ozone layer will probably collapse after a large impact for several reasons noted below. Loss of ozone will also lead to a cooling of the stratosphere. These processes will force the development of ice particles and favor rapid removal of the water.

Although strong greenhouse heating due to enhanced water vapor amounts seems unlikely to us, the possibility cannot be easily discounted in a quantitative fashion, especially since the amount of water in the atmosphere is not strongly constrained at present. This interesting idea of Emiliani and others (1982) certainly deserves further consideration.

In addition to changes in thermal structure, a large impact would alter atmospheric chemistry. Turco and others (1981, 1982) have shown theoretically that the 1908 impact of the Tunguska object may have generated large quantities of NO, which would subsequently have reduced ozone levels in the Northern Hemisphere by as much as 30% for several years. They also presented evidence showing that such an ozone reduction may actually have occurred.

The amount of NO production depends upon the energy transferred between the impacting body and the atmosphere. The Tunguska object coupled 99% of its 10^3 megatons of energy to the atmosphere. The meteoritic object being considered here had 10^5 times the Tunguska energy. On entry into the atmosphere it probably coupled its energy to the atmosphere very poorly. However, O'Keefe and Ahrens (1981) concluded that 10% to 50% of the initial energy was transferred to the atmosphere by the ejecta which travels through the atmosphere at km s^{-1} speeds. Very large quantities of NO could thus be produced. If large quantities of water are injected which subsequently form clouds and rain, then much of the NO could be removed as nitric acid.

If large quantities of NO are produced, then ozone depletion in excess of 90% would probably occur for several years after the event (Turco and others, 1981, 1982a). NO_2 produced by the event might also create large visible optical depths. In addition, the nitric oxides formed would exceed the current annual total amount of nitrogen fixed by biological organism by as much as 3 orders of magnitude. Such large quantities of fixed nitrogen might have significant effects on the biota.

At present the biological record near the Cretaceous/Tertiary boundary is the subject of considerable debate. It is difficult to draw conclusions about the cause of the extinction from the biological record. It is apparent that in the ocean, which has the most continuous record, a sudden widespread extinction of plankton occurred (Thierstein, 1981). According to Smit and Hertogen (1980), extensive foraminiferal extinctions occurred in less than 50 years. Land plants show no evidence of sudden extinction but rather gradually changed (Hickey, 1981). The majority of investigators believe that the extinctions of large animals such as dinosaurs were gradual (Tappan, 1981; Schopf, 1981). During the final millions of years of Cretaceous time, a large sea that covered much of the Earth's continental surface regressed. Perhaps 90% of the shallow coastal environments on Earth were eliminated. Most gradualists believe that the removal of these seas was primarily responsible for the extinctions. Others think that the great change in environment did not lead to extinction, but rather to a great reduction in the available fossils. Hence, these investigators believe that a sudden extinction of large animals could have occurred at the Cretaceous/Tertiary boundary (Russell, 1979). Raup (1981) has shown that environmental changes eliminating all the creatures over quite large fractions of the Earth, but not over the remainder, do not lead to massive extinctions because of the wide geographic distribution of species. Hence, simply eliminating a large fraction of a habitat would not lead to a massive extinction unless the animals were unable to survive in the remaining habitat for some reason.

A detailed investigation of the biological implications of our work will have to be carried out by specialists in the paleontological record. However, we believe that a general outline of the effects of low light levels and cold temperatures on the biological system is relatively straightforward.

We suggest that the oceanic extinctions were triggered by several months of darkness, which led to a collapse of the food chain through the photosynthetic organisms. Milne and McKay (1981) have made numerical models of the current marine food chain. They concluded that blackouts lasting 1 year would cause total extermination of marine life in tropical waters, since top predators can only endure about 6 months' starvation. Even blackouts lasting a few months are sufficient for the zooplankton to have devoured the available phytoplankton and to then starve.

The expression of the collapse of the food chain in the fossil record will depend strongly upon the ability of various creatures to survive through dormant stages. Many forms of plankton have cysts and so would survive a period of blackout. Likewise, creatures such as sharks can starve long periods and also may lay eggs which might allow them to repopulate if the adult forms starved.

On the land the absence of light would probably not cause a collapse of the food chain as was suggested by Alvarez and others (1980). The biomass on land is much larger than that in the ocean. It would require several years for animals to eat the available plant stock and begin to starve. Temperate land plants would survive a short duration blackout as they now survive winter. Tropical species would be able to reseed themselves and so repopulate.

If massive extinctions of large land animals did occur at the Cretaceous/Tertiary boundary, we think it had two causes. First, the low light levels would have made vision impossible so that it would have been difficult for large creatures to locate food. Second, the sub-freezing temperatures would have killed any creatures that were not cold adapted or did not have a place to hide. Small creatures would have more easily survived because they would be more numerous, enhancing the probability of a few living; they would be able to escape low temperatures by moving 6 inches or a foot underground, and would more easily be able to stumble upon enough food to sustain themselves.

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